Graphene Core 1

Graphene-Based Disruptive Technologies

Horizon 2020 RIA

WP19 Research Management

Deliverable 19.4 “Updated S&T Roadmap”

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Due date of deliverable: M24

Actual submission date: M24

Dissemination level: PU

Funded by
the European Union

Project funded by the European Commission under Grant Agreement n°696656

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<ins>Updated S&T Roadmap:</ins>

Graphene and other 2D materials Technology and Innovation Roadmap

Version 3, March 2018

Summary

Core 1 brought a substantial upgrade to the TIR regarding both advanced methodology and in-depth analyses enabled thereby. Based on the comprehensive evaluation of all major GRM application areas, four initial highlight application scenarios have been selected for in-depth investigation of the envisioned value chains. The novel Innovation Interface Investigation (3I) approach uncovered direct and indirect GRM innovation opportunities and challenges related to (a) supercapacitors, (b) anti-corrosion coatings, (c) Li-ion batteries, and (d) neural interfaces. Expert perspectives from various end user contexts such as warehouse logistics, marine, automotive, wearable devices, or neural therapy were directly involved in the evaluation. Key drivers of GRM diffusion include emission prevention and digitisation in the logistic sector (a), mechanistic explanation of long-term corrosion protection (b), desire for advanced charge rate and energy density (c), and advanced neural interface capabilities, enabling new markets (d). The aggregation of specific GRM commercialisation needs and demands from the industrial downstream markets considered in the focus analyses served as the starting point for a new TIR chapter on the graphene materials supply market. Beyond our graphene production roadmap based on the consensus expectations of the industry experts consulted in our 3I studies, we also conducted a survey of GRM-related product innovations, implemented a new meta-market analysis concept, and discussed the results in light of the established international innovation landscape indicators such as transnational patents or peer-reviewed publications. Common challenges for GRM commercialisation include production volume expansion, cost reduction, immature market status, insufficient material specifications, lacking consistency of supply, and the definition of application specific KPI and their transfer into accepted key control characteristics (KCC).

1. Objectives

The Technology and Innovation Roadmap (TIR) within the Graphene Flagship aims to guide the community towards the development of products based on graphene and related 2D material (GRM). The TIR goal is to outline the principle rules to develop the GRM knowledge base, the means of production, and development of new devices, aiming at a final integration of GRM into systems. The TIR addresses three major target groups: (a) the internal Graphene Flagship community; (b) external research communities; and (c) industry (promoting the recognition of future GRM application potentials). In this sense, the TIR aggregates a common view on GRM and provides guidance for graphene research towards market demands. Beyond a general update, the present TIR aims at an upgrade, comprising a deeper understanding of specific highlight GRM applications. Based on a novel methodology, a first set of focus studies were implemented, and their results integrated into the TIR.

2. General Approach and Novel Methodology

In extension of the initial Science and Technology Roadmap, the TIR format takes into account how technology supply could meet industrial demand with a focus on economic aspects and non-technological frame conditions. The TIR approach comprises a combination of science/ technology supply and market needs perspectives. Science and technology supply will merge with market demand at the level of different application areas (Figure 1).

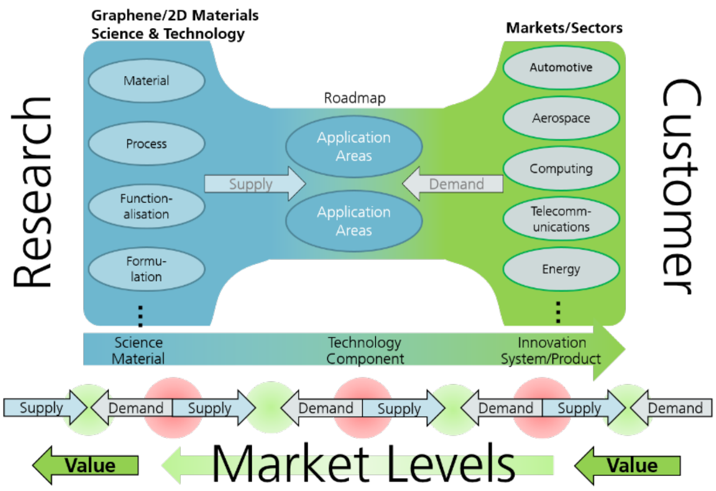

Figure 1: General roadmap approach and refinement strategy.

This fusion approach guides the way from science providing GRM material, to technology designing GRM-based components, to innovation in the form of new systems and products. The first update covered a broad approach in a way that all promising application areas for GRM were analysed, however, at a limited level of detail. Hence, the present version (second update) now also includes novel methodical concepts for in-depth analysis of specific focus application areas: the long journey from graphene research to product innovations spans several market levels with their own supply and demand dynamics. Indirectly, final customer demands influence all subsequent market levels. The economic prize of the final product reflects the added value that is passed back throughout the physical supply chain.

2.1 Innovation Interface Investigation (3I)

Typically, it will require several distinct integration steps along a prospective value chain to trace the potential advantages of graphene in the context of a final product category. In order to understand and promote emergent innovation processes based on graphene, we developed the versatile Innovation Interface Investigation (3I) scheme. 3I enables analysing and understanding the exchange and learning processes between different innovation agents.

2.1.1 Innovation Spheres

We identify and define Innovation Spheres to consist of individuals and entities sharing a rather similar body of expertise, knowledge, capabilities, and interests. They gather a stakeholder group from a concise industry segment targeting a certain product category based on a specific technology. Depending on the level of maturity, on outsourcing and vertical integration status, on market size and characteristics, as well as on various other parameters, both the extent and volume of the Innovation Sphere and the clarity of its borders may vary significantly. Large and mature Innovation Spheres often consist of several sub-spheres that may co-exist within a single corporate entity. Hence, the Innovation Sphere definition largely depends on context and scope, and may be split or merged to serve as the basic elements to define and map innovation networks that reflect the emergence or transformation of value networks based on the availability of the new materials, technologies, or concepts in consideration.

2.1.2 Innovation Interfaces

We refer to actual and potential interactions between Innovation Spheres as Innovation Interfaces. These constitute around existing or conceivable future supply and demand relations between entities from neighbouring Innovation Spheres. Mature industries operate in complex innovation networks, where specific entities from neighbouring Innovation Spheres often execute bi-lateral R&D initiatives under strict non-disclosure terms. In contrast, most GRM applications still reside in a much earlier innovation stage, where they may initiate novel products and value chains or transform existing ones. Of course, new industries evolve in the direct context of the emergent innovation, but we still lack sufficient knowledge of their extent and limitations. Benefits and drawbacks remain unknown or highly speculative. Considering the extent and effort required in the existing industrial innovation and qualification cycles, large-volume application of the aspired innovations often lies at least 5-10 years ahead. The intended applications remain largely subject to scientific research and public funding initiatives, and to curiosity and scepticism within indirectly involved Innovation Spheres.

2.2 Focus Research

Following the 3I scheme, the TIR focus research initiatives consist of four consecutive phases: (i) Conception – establishing draft concepts of involved innovation spheres by elaborating a conceivable future value chain for a specific graphene application based on desk research. (ii) Consultation – informal and confidential exchange with key experts along the innovation chain, aiming at critical discussions of prospects, issues, and framework conditions regarding the subject matter. (iii) Interactive 3I workshop – assembly of all relevant perspectives based on a careful selection of participants from each Innovation Sphere. Confidentiality agreements and group size foster open discussion. Explicit goals include (a) identification of present status and anticipated developments in the individual key industries, (b) definition and critical discussion of common KPI across the Innovation Interfaces, and (c) technologic, economic, and temporal alignment of perspectives. Implicit goals include exchange of information and perspectives along the envisioned innovation chain to uncover collaboration potentials and future market advantages. (iv) Documentation – information aggregation in a concise report validated by an extended expert pool. Earlier TIR results served as a major guidance criterion for the selection of an initial topic set for focus investigations following the 3I scheme.

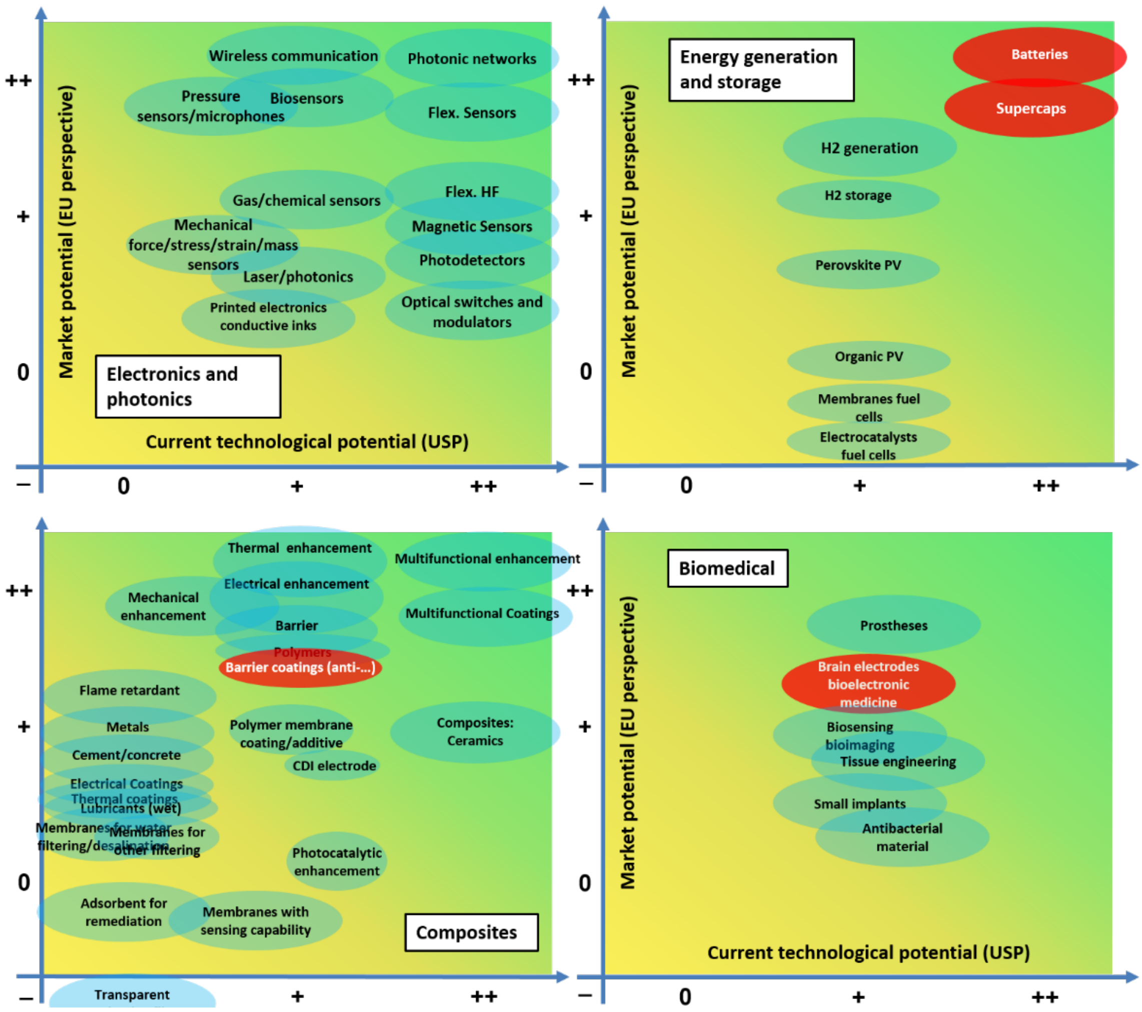

Figure 2: Portfolio overview of the most promising graphene applications according to TIR results.

Focus topic	Supercapacitors	Anti-corrosion	Li-ion batteries	Neural interfaces	Total
Direct Innovation Interface	Electrodes for supercapacitors	Novel anti-corrosion coatings	Electrodes for Li-ion batteries	Medical research and evaluation	
Indirect Innovation Interface	Forklifts, Warehouse logistics	Aerospace, Automotive, Marine	Automotive, Wearable devices	Advanced neural therapy	
Experts consulted	42	47	43	48	180
- from industry	37	33	29	23	122

- from flagship	8	9	21	11	49
Experts selected	20	23	24	23	90
Workshop date	July 4th, 2017	Oct. 24th, 2017	Nov. 28th, 2017	Jan. 25th, 2018	
Participants	19	22	21	19	81
Workshop location	THE SQUAIRE Conference Center, Frankfurt Airport, Germany				

Table 1: Overview on focus investigations carried out during Core 1 phase.

The portfolio analysis in Figure 2 summarises possible graphene applications and their evaluation based on the assigned technological potential and European market perspective compiled by major application areas. The red colour highlights the selection of initial focus investigation topics already covered in the present TIR update. The final selection also took into account further input gathered from the Graphene Flagship's technical WPs, as well as research, experience, and insights of the TIR team. Close coordination with WP innovation was established and will be further refined in the future. Table 1 summarises the implementation details for all four 3I focus studies executed during Core 1.

3. Graphene Market Status and Prospects

A new TIR chapter combines general graphene production and commercialization aspects regularly raised in different focus investigations with a current product status survey and aggregated market expectations to provide an overall picture of the economic potential.

3.1 Graphene Production Roadmap

The commercialisation of graphene served as a starting point of all innovation chains in all focus investigations carried out within the present TIR phase. The initial Innovation Sphere always covered the production of graphene, and the peculiarities of its (potential) supply to downstream Innovation Spheres constituted major aspects of the direct Innovation Interface. In every focus investigation, the insufficient maturity of the graphene industry was identified as a major threat and critical bottleneck for the commercialisation of graphene-based products. The graphene production roadmap in Figure 3 summarises graphene commercialisation targets based on expert expectations gathered throughout all focus investigations.

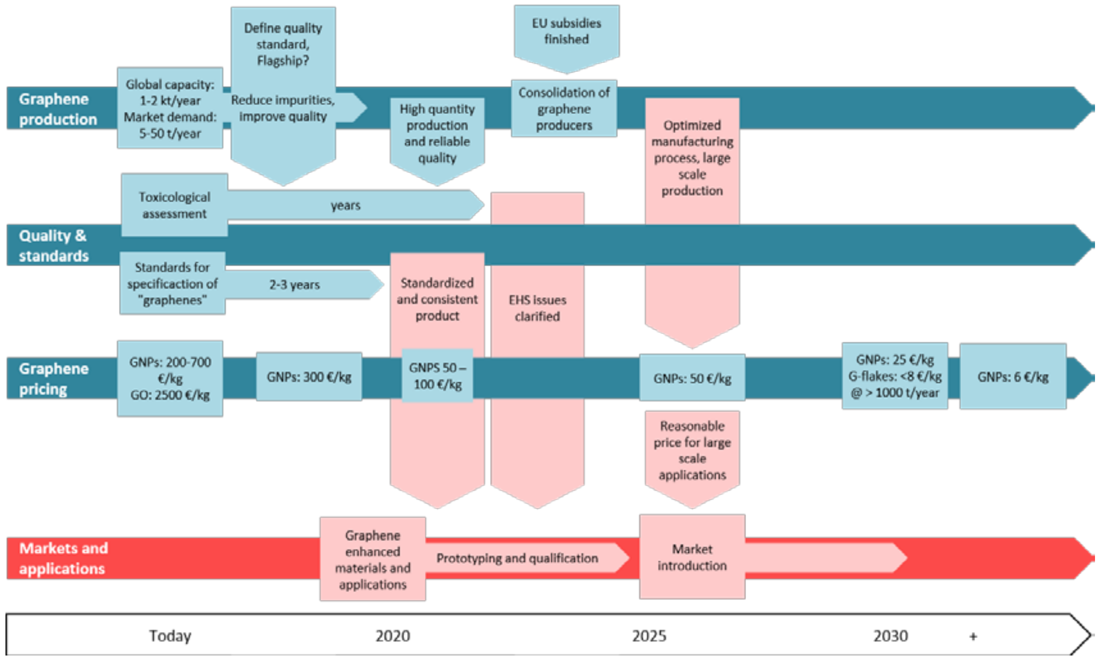

Figure 3: Roadmap for graphene materials suppliers aggregated from all executed 3I focus studies.

Beyond the expansion of production capacity and simultaneous price reductions, key factors for the commercialisation include (a) regulatory hurdles (such as REACH) associated with the unresolved toxicology, (b) a lack of standardisation and reliability (see below), and (c) technical demands to graphene properties often only defined in the specific application context.

3.1.1 Standardisation, Specification, and Quality Assurance

At present, no generally accepted specifications of graphene in terms of material supply and product quality exist. In Europe, application ideas and products often emerge from start-ups or university spin-offs based on promising lab results. Both materials synthesis and characterisation usually follow unique protocols, further impeding direct comparison of results. Hence, (potential) GRM users find it challenging to select the right materials for their application from the range of "graphenes" available on the market. Both GRM producers and downstream users that participated in our focus studies assessed a standardised nomenclature for materials and characterisation parameters as critically important to define product relevant key control characteristics (KCC). In practice, quick high-throughput techniques appear necessary to establish practicable KCC and confirm compliance with quality control mechanisms.

3.2 Products, Patents, and Publications

The TIR process includes continuous publication and patent monitoring. Results also appear in the full roadmap document (compare Annex), but a separate monitoring report constitutes another deliverable (submitted in M12). Hence, the present document only includes a brief rationale (Figure 4) important for the context. D16.2 in WP16 contains further information on the external innovation landscape.

A product survey constitutes a novel feature of the present TIR iteration, for which available products and product development announcements involving GRM have been systematically tracked and evaluated. Among 43 independently verified product developments, European actors launched a vast majority (31). This might be an indication for a direct economic impact of the Graphene Flagship, in particular, as partners are directly affiliated to nine records. However, a language bias (survey conducted in English) may specifically underrepresent Asian actors. In reference to the patent counts (see Figure 4), the different framework conditions (dominance of public vs. private sector between EU and US) may also induce different publication strategies.

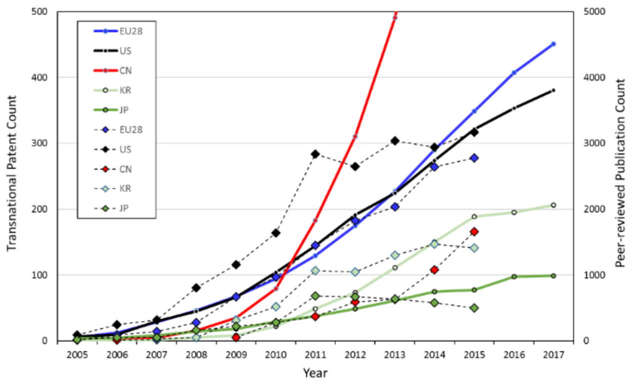

Figure 4: External innovation landscape based on publication (solid) and patent (dashed) records.

3.3 Meta-market Analysis

Initial graphene-based technologies and products actually reaching the market mark an early diffusion stage, where sustainable economic interests slowly develop. Accordingly, an increasing number of market studies become available and offer market predictions. In this context, we developed a novel methodology that analyses the variety and development of market studies, checks their reliability, and aggregates key results. Figure 5 summarises the most relevant figures regarding the expected development of the graphene market.

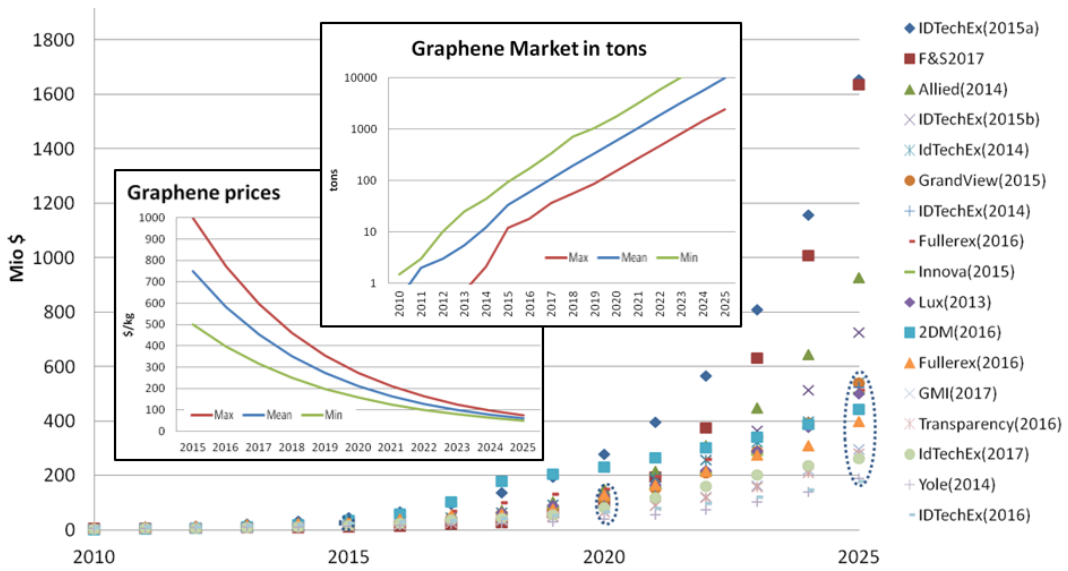

Figure 5: Meta-market analysis combining market expectations from multiple market studies predicts significant growth of the graphene market, but also reveals major prediction uncertainty. The inset shows the derived decay of the graphene unit price and the expansion of the production volume based on the most extreme predictions (min/max) and a derived trend scenario (mean).

4. Graphene Applications

The current TIR covers 73 promising application areas for GRM, so far, four specific application scenarios have been analysed in-depth by novel 3I techniques. The present document only features a coarse summary; the annex to this deliverable covers the detailed analyses.

4.1 Composites and Coatings

Enhanced functionality motivates the potential use of GRM as additive to composites or coating layers. GRM incorporation in **composites** enables a multitude of application opportunities with rather low technical requisites (platelets may often suffice), but high economic sensitivity (low price, high volume). Important topics include functionalisation of GRM for achieving optimum dispersion, potential environmental and health risks, and public perception ranging from 'wonder material' to 'the next CNT'. This also applies to the **coating and paint** sector at a different cost-benefit relation (see below). GRM use as an additive to **liquids** features even lower implementation barriers, e.g. for drilling fluids. Other application areas include functional **membranes** (de-salination, water purification) or **photocatalytic** use in combination with TiO_2.

4.1.1 Focus: Anti-corrosion in Aerospace, Automotive, and Marine Contexts

Corrosion causes significant damage throughout the economic system on a global scale. Thus, control and prevention of corrosion impacts implies huge markets for the paint and coating industry, but anti-corrosion solutions usually only constitute a minor side aspect at the end user level. Established and sufficient technologies usually exist, and end customers are highly reluctant to accept/embrace changes, but environmental impacts drive stricter regulation, abruptly enforcing transformation. Actors along the innovation chain anticipate upcoming change due to technical and regulatory developments. This creates opportunities for novel anti-corrosion solutions based on GRM once their functional principles are established and the efficacy of products verified. At present, controversial discussion regarding anti-corrosion functions of graphene takes place in the scientific literature. Some consensus exists on beneficial barrier properties, but electro-chemical aspects remain highly disputed. Even in case clearer scientific results appeared, the paint industry would require improved graphene materials supply (see section 3.1) to engage in early upscaling tests. A sound mechanistic understanding of the underlying anti-corrosion mechanisms would not only support the product process, but also constitute a key requisite for market entry as customers request convincing proof of long-term function.

4.2 Energy

In general, energy applications potentially open up distinct high-volume markets for GRM in a field of high innovation affinity. Novel technologies may disperse quickly if backed by a unique selling proposition and by competitive cost-benefit relations. Two-focus investigations cover **energy storage** applications (see below). In the energy conversion sector, GRM appear highly promising as electrocatalyst for **fuel cells**, where they may unlock significant cost reduction potential in the case of replacing noble metals such as platinum. However, the technical progress with fuel cell vehicles may suffer from public and political preference currently given to battery electric vehicles. In renewable **energy generation**, GRM hold significant promise in the **photovoltaic** sector as potential replacement of transparent conductive oxide top contacts, but more mature technologies such as silver nano-wires constitute tough competition. Innovative perovskite solar cell technologies may compete with or complement the dominant material standard (silicon) and GRM may serve as an enabler for charge collection.

4.2.1 Focus: Advanced Li-ion Batteries for Consumer Devices and Traction

Strong trends towards mobile consumer devices and electro mobility generate a rapidly increasing demand for electricity storage primarily catered by Li-ion batteries (LIB) today. The market is highly competitive regarding both unit price and technical performance. In particular, novel applications may require advanced function, opening specific opportunities for graphene: energy density enhancement requires increased silicon incorporation in anodes, but affects their durability. Graphene incorporation may be a lever to counter balance anode integrity. Many applications require fast charge rates, where graphene might offer a unique selling proposition, too. On a global perspective, present LIB production is largely concentrated in Asia. Strong political and corporate interest push towards creating a European manufacturing base. Graphene-enhanced LIB might serve as a market entry point for new European players, but established Asian producers will certainly provide fierce competition.

In light of the technical promise of graphene for LIB and the competitive global market, the Graphene Flagship decided to launch a dedicated innovation development initiative (among several other Spearhead projects) for Core 2. In collaboration with both WP16 as well as the upcoming Spearhead, we further refined the 3I concept in order to align all internal forces dedicated to the subject matter and maximise synergy.

4.2.2 Focus: Supercapacitors for Forklifts and Advance Warehouse Logistics

Supercapacitors feature superior power density and cycle-life compared to LIB, but do not reach their power density. Hence, the emerging industry only caters niche applications so far. The energy density of future supercapacitors will likely advance based on electrolyte (higher cell voltage) and electrode material (higher capacity) innovations. Graphene is a promising candidate in the latter regard, and its incorporation in electrode compounds may increase both power and energy density as well as thermal robustness of the devices. Several European supercapacitor producers address niche markets and push for mass applications. Early adoption by the strong European forklift industry might create mutual benefits: the progressing electrification of forklifts calls for improved energy storage solutions; a new trend towards automated warehouse solutions based on smaller automated guided vehicles particularly demands the characteristics of supercapacitors. Small European producers may benefit from an early European volume customer base. Their limited R&D capacities, however, do not support extensive graphene qualification initiatives, requiring interested materials suppliers to put extensive effort in dedicated supply and development towards the specific technical needs.

4.3 Electronics and Photonics

Diverse GRM applications may occur in telecommunications, optoelectronics, photonics, computing, sensors, and flexible and printed electronics. Most require the highest material quality such as single-layer graphene with low or no tolerance for defects. Wafer-scale integration is a significant challenge and induces high time to market. **Cross cutting issues** address front-end-of-line and back-end-of-line as well as packaging in semiconductor fabrication. GRM hold promise in **optoelectronics** for high-speed communication, and mobile **telecommunication** (5G and beyond) appears particularly relevant for the European economy. The absence of a bandgap disqualifies graphene for classical **computing** applications, but functionalisation and other 2D materials appear promising for logic circuits in the context of further progressing miniaturisation. Global trends such as the Internet of Things, Industry 4.0, mobile electronics, or autonomous driving, drive a mass market for various integrated **sensors**, whilst granular niche markets enable diverse opportunities for early market entry of innovative GRM-based solutions. The juvenile market of **flexible and printed electronics** sets low entry barriers for GRM, and the first conductive inks based on graphene are already commercially available today.

4.4 Biomedical

Medical devices benefitting from GRM-based coatings, composites, or sensors, may be closest to market. Unique emerging applications in the biomedical field include flexible, wearable, and mobile devices, as well as drug delivery. Pharmaceutical and medical device markets feature exceptional regulation, thus require extensive proof of quality, safety, and efficacy.

4.4.1 Focus: Neural Interfaces for Pre-clinical Devices and Advance Neural Therapy

Noble metal devices with severe restrictions regarding electrode density and function dominate the medical neural interface market today. Advanced neural therapy, electrotherapeutics, and brain-machine interfaces necessitate overcoming these limitations and promise attractive future markets. Graphene combines highly desirable impedance, conductivity, charge-transfer, and biocompatibility characteristics, but the small and scattered European research community needs to combine efforts to compete with US actors. Strict market regulation creates significant bias against SME in the field despite explicit dedication of EU research funding intended in their favour. This points to a need for improving the respective innovation ecosystems.

5. Conclusions

GRM are still a young and emerging class of materials. Early products hit niche markets, mostly based on graphene flakes. The TIR spans the large and diverse variety of GRM application areas, addressing many different markets and needs. Many companies prefer to observe the GRM field awaiting higher maturity and investigate competing technologies. In the electronics sector, flexibility, high electron mobility, and optoelectronic properties create USP for GRM, but commercial feasibility of wafer scale integration represents a major barrier.

Focus investigations following the novel 3I scheme enable in-depth resolution of potential future European value chains and promote early exchange of information and perspectives through emerging innovation interfaces. Common challenges regarding GRM materials supply do not only concern production volume expansion, cost reduction, and quality improvements, but always point to the immature market status with insufficient or absent commercial GRM specifications, lacking reliability of supply, and the definition of application specific key performance indicators as critical inhibitors of the emerging commercialisation of graphene.